OPTICAL EMISSION SPECTROSCOPIC EXPERIMENTS FOR IN-FLIGHT ENTRY RESEARCH
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ABSTRACT

The present paper provides an overview of past optical emission spectroscopic experiments dedicated to the investigation of aerothermodynamics of atmospheric entry. The total and spectral radiation measurements of the experiment FIRE are addressed as well as Bow Shock UV (BSUV) / UV Diagnostics Experiment (UVDE) and a summary of the spectroscopic experiments of the airborne observation campaigns for Stardust, ATV1 Jules Verne and Hayabusa. The focus of the paper is on the presentation of the recently developed emission spectroscopic experiment RESPECT. Sensor system design and measurement specifications are described. In addition, an outlook on the post flight data analysis and expected results is given.

1. INTRODUCTION

Thermal protection systems (TPS) of space vehicles are exposed to significant mechanical and thermal loads when entering the atmosphere of a planet. Primarily these loads are defined by the plasma state of post shock regime and boundary layer which are mainly governed by the inflow conditions and the vehicle geometry. In addition to pressure loads and convective heating, radiation heat flux can be one of the major design drivers for TPS layout. Significant contribution of the radiation heat flux to the total heat flux on a vehicle surface is expected for high speed entries, typical for sample return missions or entry missions to the giant planets.
In order to predict the loads on thermal protection systems of entry vehicles, numerical tools to simulate the complex conditions in post shock regime and boundary layer are widely used. Hence, in the past, various numerical codes have been developed to simulate the flow field and subsequently the radiation emitted by the plasma species. Unfortunately, as it is not possible to re-produce all influencing parameters in ground test facilities at the same time, verification and improvement of the existing codes using ground based experimental data is limited. Thus, in-flight measurements are most valuable to increase the reliability of the current data base.
Optical emission spectroscopy represents a smart, sophisticated tool to gather qualified data sets, containing both information on plasma state and emitted radiation. The high value of emission spectroscopic data measured during entry manoeuvres becomes obvious when looking at the FIRE II data. The spectroscopic data recorded during the FIRE II re-entry is still intensively studied and, although more than 40 years old, is still used as a reference test case for radiation simulation tools. Further evidence of the high significance of emission spectroscopic data is given by the large number of spectroscopic experiments participating in the latest airborne observation campaigns of Stardust, ATV1 Jules Verne and Hayabusa.
A future project, dedicated to investigate numerous aerothermodynamic problems is the European EXPERT mission [1]. One of the 14 payloads is a spectrometer system named RESPECT developed to build a database on emission spectroscopic data during re-entry of the EXPERT vehicle.

2. OVERVIEW OF PAST OES EXPERIMENTS FOR RE-ENTRY APPLICATON

In the past, only a very limited number of experiments measuring spectrally resolved the radiation emitted by the plasma surrounding a space vehicle during atmospheric entry was realized. In-flight experiments installed onboard the space vehicle itself are limited to the measurements performed within the project FIRE [2]. Considering measurement of the total radiation heat flux, meaning a broadband measurement integrating over a wide spectral range using radiometers, the list of in-flight measurements can be slightly enlarged. Like the FIRE I and FIRE II re-entry vehicles, for instance, the Apollo Command Modules

of Apollo 4 and Apollo 6 were equipped with radiometer gauges [2, 3].
The majority of optical emission spectroscopic experiments performed in the context of atmospheric entry are part of airborne observation campaigns. Although airborne observation has some unavoidable disadvantages, it has been performed quite frequently in the past years. Compared to onboard experiments, the disadvantages are the rather large distance to the measurement object complicating spatially resolved measurements and the negative influence of atmospheric signal extinction. In particular, VUV emission is blocked by absorption caused by the atmosphere and can only be realized by onboard experiments. In addition, the entry trajectory of a space vehicle can not be covered completely by airborne measurements. On the other hand, airborne experiments are less restricted in terms of volume, mass and electric power. Furthermore, mechanical and thermal loads on the measurement equipment are almost negligible. But the strongest argument for airborne observation campaign is that re-entry manoeuvres can be investigated in detail, which suffer from a lack of onboard instrumentation. The latest campaigns were dedicated to the re-entry of Stardust [4], ATV1 Jules Verne [5] and Hayabusa [6]. Similar to the airborne experiments is the observation of a re-entry vehicle from a space platform. An example is the observation of the Soyus-TM and ATV Jules Verne re-entries using the instrument FIALKA aboard the ISS [7].

2.1 FIRE I and FIRE II Spectral Radiation Measurements

In preparation of the Apollo flights, project FIRE aimed on the determination of radiative and total heat flux on a blunt re-entry vehicle entering Earth's atmosphere at hyperbolic velocities [9]. In preparation of the later Apollo re-entries, the vehicles had a nose radius of 0.935 m and their geometry was very close to the Apollo shape. Two flights in 1964 and 1965 were conducted. The FIRE I re-entry point at an altitude of 122 km was characterized by a velocity of 11.57 km/s and a re-entry angle of -14.6°. The trajectory of FIRE II was slightly changed. At the re-entry point at an altitude of 122 km, the velocity and re-entry angle were 11.35 km/s and -14.7°, respectively. The radiation has been measured with a spectrometer and two radiometers. The radiometers analysed the total radiation in the wavelength range $200\ \text{nm} < \lambda < 4000\ \text{nm}$ at two positions at the front side of the vehicle. The spectrometer and one total radiometer shared the stagnation point for measurement. The measurement position of the second radiometer was about 18° offset from the stagnation point. In addition, a third radiometer measured the radiation heat flux on the rear side of the vehicle [9]. The spectrometers covered a wavelength range of $200\ \text{nm} < \lambda < 600\ \text{nm}$ and provided a spectral resolution of 4 nm. The instrument was designed as a scanning spectrometer. Difficulties with the scanning mechanism during FIRE II flight limited the usable spectral measurement range to about $300\ \text{nm} < \lambda < 600\ \text{nm}$ [10]. The mission design with a layered heat shield, an alternating sequence of calorimetric and ablative layers, provided three measurement periods with a "clean" environment, corresponding to the calorimetric layers [11]. These periods are characterized by a flow without erosion products originating from the ablator. In addition, the absence of erosion products guaranteed clean windows for the spectral and total radiation measurements. The trajectory periods providing clean environment are summarized in Table 1 for FIRE I and FIRE II. The data periods 2 and 3 of FIRE I failed due to a movement of the ablation shield causing the optical port to be blocked [10].

Data Period	Altitude / km	Velocity / km/s
Fire I		
1	89.01 – 70.00	11.63 – 11.53
Fire II		
1	83.75 – 69.80	11.37 – 11.30
2	54.34 – 53.23	10.61 – 10.51
3	41.80 – 40.75	8.20 – 7.74

Table 1. Project FIRE data periods of spectral radiation measurements [10, 11, 12].

Nevertheless, these measurements were a remarkable success. The instruments provided intensity data with spectral distribution of the incident radiation. The data periods covered non-equilibrium flow regimes as well as flow conditions considered to be prevailed by equilibrium temperatures. The spectral data of periods 1 and 3 is dominated by emissions from N_2^+ (1^{st} neg.) whereas data period 2, corresponding to peak heating, is dominated by continuum radiation [10]. The Fire II absolute and spectral radiation measurements belong to the most significant aerothermal in-flight experiments realized. The data gained, although more then 40 years old, is still extensively studied. Not only the consideration of the data as a test case for coupled flowfield/radiation measurements proves its high value. Extensive numerical investigations to rebuild the FIRE II measurement data was only recently published for example by Park or Merrifield [3, 8, 13].
Although the measured spectral radiation data is very valuable, some improvements for future spectrometry instrumentations are recommended: For example, a

more detailed in-flight characterization of the catalytic and optical properties of the TPS surface is requested. An extension of the spectral range towards VUV and a higher spectral resolution are the most desired upgrades. The importance of VUV radiation was only recently shown by Merrifield and Fertig when numerically simulating the FIRE II re-entry. One of the results was that for the trajectory points investigated up to 90 % of the total radiation heat flux in the stagnation point was emitted in the VUV wavelength interval between 80 nm and 200 nm [8]. Furthermore, if VUV radiation is studied, it implies that the flow chemistry must be addressed, too. In particular, gas surface interaction, defining composition and temperature of the boundary layer must be considered. The absorption of the radiation is mainly defined by these properties, thus an influence on the radiation heat flux is evident [8]. But also the convective heat flux is influenced, as shown by Merrifield and Fertig [8]. Thus, future in-flight experiments dedicated to the measurement of VUV radiation would be of great value. The concept of such a mission was developed within the ESA RadFlight study, addressing among other things the measurement of spectrally resolved and total VUV radiation in a, with respect to gas-surface interaction, rather simple environment by applying a C/C heat shield [14].

2.2 Bow Shock UV and UV Diagnostics Experiment

Another series of experiments to gain a deeper insight into radiative effects within the post shock regime were the two sounding rocket experiments Bow Shock UV (BSUV) in 1990 and the UV Diagnostics Experiment (UVDE) in 1991[15, 16]. It was attempted to measure the bow shock ultraviolet radiance, mainly the emissions from the NO gamma band system.

The first experiment, BSUV, was launched on a two stage Terrier Mamalute rocket. At an altitude of 37 km, the rocket reached a velocity of about 3.5 km/s, which was kept almost constant up to an altitude of 75 km. The period of constant velocity (38 km – 70 km) during ascent was used for measurements with the scientific instruments. The upper stage, with a blunt nose of radius 0.1016 m, was equipped with one spectrometer positioned in the stagnation point and eight radiometers under different viewing angles of 0°, 30° and 50° with respect to the vehicle center line. A spectral range of $190\ nm < \lambda < 400\ nm$ with a resolution of 1 nm was accessible by the spectrometer in modified Fastie-Ebert design. The radiometers covered primarily the spectral range of $\lambda = 230$ +/- 30 nm associated with the NO γ system. Furthermore, radiometers for $\lambda = 215$ +/- 3 nm (NO gamma (1, 0)), $\lambda = 309$ +/- 4 nm (OH A-X (0, 0)) and $\lambda = 391.2$ +/- 1.5 nm (N_2^+ 1st neg. (0, 0)) were installed. In addition, a NO-filled CaF_2 window ionization chamber acting as a detector for atomic oxygen based radiation in the vacuum ultraviolet (O I 130.4 nm) was part of the optical experiments. The instrumentation was completed by a Langmuir probe to measure electron density and temperature [15].

UVDE shared the same geometry with BSUV but the trajectory was optimized towards higher speeds, accomplished by a three stage design of the sounding rocket. The first stage Castor I booster lifted the payload to an altitude of about 120 km. The second-stage Antares II and third-stage Star 27 engines were used to accelerate the payload during descent to a velocity of 5.1 km/s which was kept almost constant down to an altitude of approximately 62 km where the payload was destroyed due to structural failure. The instrumentation was similar to the BSUV experiment. The applied spectrometer had identical characteristics and also the radiometers measured the same NO, OH and N_2^+ molecular features with a slightly smaller spectral range and more emphasis on the OH radiation. Furthermore, apart from the O I 130.4 nm VUV sensor, a second instrument dedicated to hydrogen H I 121.5 nm was installed [16].

The experiments aimed on in-flight measurement data associated to re-entry conditions different to the hyperbolic conditions of FIRE I and Fire II. In particular the low-speed and low-altitude flight regimes were addressed in order to allow for tests of the chemical and radiation models originally developed for high-speed flight regimes. Both experiments, BSUV and UVDE, were successful and provided the desired data. The numerical rebuilding of the BSUV spectral measurements was very successful for the lower altitude measurements but differed significantly at higher altitudes [17]. The thereupon made improvements on the numerical codes included consideration of rotational non-equilibrium, improved reaction rates for the production of NO and electronic excitation due to heavy particle collisions [18]. Thus significant improvement of coupled CFD/radiation simulations in the low-speed, low-altitude flight regime was achieved.

2.3 Airborne OES Experiments for Stardust, ATV and Hayabusa

Since 2006, there have been three airborne observation campaigns where IRS participated dedicated to the observation of re-entry vehicles, the reason for it being the fact that the re-entering vehicles had no on-board equipment to probe the performance of the heat shield.

The airborne observation campaigns were organized as multi-instrument campaigns, where different instruments aiming for particularly observable events or characteristics have been setup in parallel. The IRS instrument for STARDUST and ATV1 was designed to measure considerably highly resolved the near UV radiation of CN and N_2 in order to gain information about the ablative processes and its interaction with plasma radiation [19, 20]. Although ATV1's purpose was a destructive entry manoeuver, again the radiation information leads to a possibility to draw a re-entry and destruction scenario for comparison to numerical tools [5, 21]. Fig. 1 shows an overview of the instruments operated for STARDUST and ATV1 as function of spectral bandwidth and resolution. The challenging task of airborne observation is the tracking of the entering object. Although the flight path of the aircraft is very well chosen in order to minimize tracking effort of the experimenter, there lasts the risk of missing the very fast entering object. Therefore, the intention of the organisation of the instruments was also to realize at least partly a redundancy.

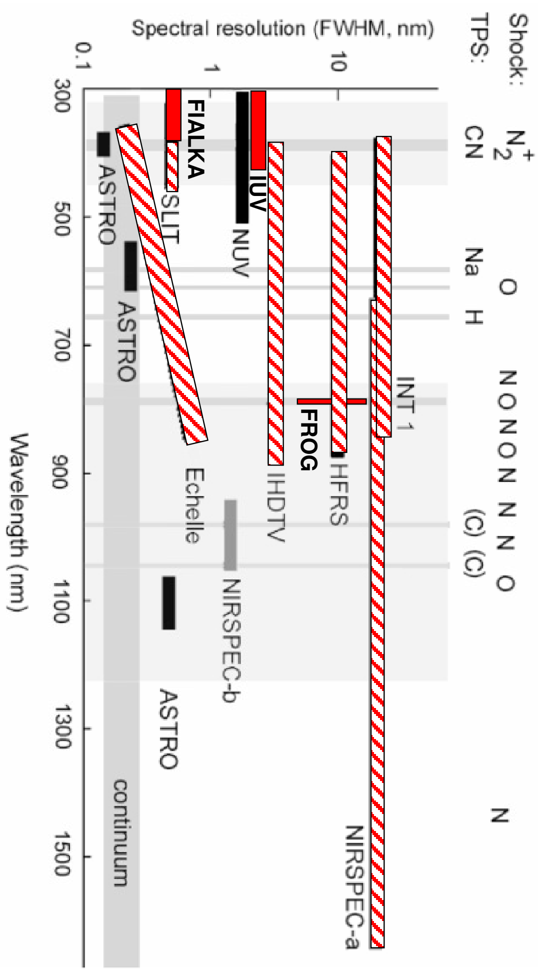

Fig. 1. Overview of STARDUST and ATV1 spectrometry experiments (STARDUST in gray, STARDUST+ATV1 hatched, ATV1 in red) [20].

The instrument applied for those two missions was based on a conventional Czerny-Turner spectrograph. This spectrometer given the name SLIT processed light collected by a fiber connected small telescope with a rather high view angle of 0.45°. The sensitivity of the instrument was increased by using an EMCCD camera type Andor DU971N. The expected intensity from the destructive re-entry of ATV1 was by far higher, therefore, the institute's ICCD camera (PI-MAX) was sufficient. Using a higher integration time during ATV1 allowed therefore higher signal intensity.

A similar manoeuvre in terms of velocity was the re-entry of Hayabusa in June 2010. Here, JAXA organised an airborne observation campaign, supported by NASA. IRS proposed for this mission a different airborne experiment compared to the SLIT instrument for STARDUST and ATV1. The background for this instrument was that results from the STARDUST observation showed that there is a significant interest in a closer understanding of the excitation processes of the atmospheric atoms during re-entry flight. The instrument proposed used a setup including a scanning Fabry-Perot interferometer aiming to measure the lines very highly resolved leading to information about the translational temperatures of oxygen and nitrogen.

Although the re-entry of the ATV was a destructive manoeuvre on purpose and thus not implicitly comparable to the other mission, it is listed here due to the very similar experiments used. In all three observation campaigns, the list of instruments is dominated by different types of spectroscopic experiments covering a wide spectral range. The spectroscopic experiments of the Stardust and ATV1 re-entry observation campaign are summarized in Fig. 1. It is highlighted, that in addition to the airborne experiments the ATV re-entry was monitored using the experiment FIALKA onboard the ISS, which was also used for measurement of UV radiation intensity along a Soyus-TM re-entry trajectory [7].

The analysis of the measurement data, primarily intensity and spectral distribution of the radiation emitted by the plasma, allowed for species identification and determination of excitation temperatures and with it inside in the thermochemical processes in the post shock regime of the respective vehicle. Due to the rather large number of OES experiments in airborne re-entry observation campaigns a more detailed review is spared but is available in [4, 5, 6]

3. THE RESPECT INSTRUMENTATION ABOARD EXPERT

A newly developed emission spectroscopic instrumentation for re-entry application, described in detail in section 3.2, is the sensor system RESPECT (Re-Entry SPECTrometer) developed at Institute of Space Systems (IRS) in the frame of the European EXPERT project to contribute to the investigation of aerothermodynamic phenomena by measuring spectrally resolved the radiation onto the thermal protection system of a re-entry vehicle. The experiment aims not on testing a certain TPS by exposing it to a significant radiation heat flux and the corresponding characterization of the flow regime. Rather, the experiment aims on building a database on spectrally resolved emission during re-entry ready for comparison with coupled flow field/radiation codes in order to allow for validation and/or improvement of current chemical and radiation models.

The instrument is designed for a spectral range of 200 nm-850 nm. Numerical simulations performed to support the optical layout of the sensor system based on trajectory predictions resulted in predicted radiance levels high enough to allow for measurements in an altitude range between 70 km down to 35 km [22]. Furthermore, the simulations showed that the measurement signal in the covered wavelength range will be dominated by the molecular radiation of NO γ and O_2 Schumann-Runge. The most significant atomic feature occurring within the pre-flight simulations is the 777 nm atomic oxygen triplet. Based on the enthalpy levels to be reached at the predicted re-entry velocity, which is comparable to BSUV, these pre-flight predictions seem reasonable.

In a straight forward approach, the measured spectra can be used to identify the emitting species and to estimate the excitation temperatures by fitting simulated spectra to measured signals. The method yields a rough picture of the plasma state in the shock region dominating the radiation and was for instance successfully applied by Winter in the STARDUST observation campaign to estimate the molecular excitation temperatures in the plasma around the Stardust SRC [23].

Nevertheless, the accuracy of such an approach is limited. The reason is the integrating character of optical diagnostic methods, resulting in a measurement signal composed of radiation gathered all along the line of sight and limited wavelength resolution. In order to gain spatially resolved information, which allows to distinguish between the conditions in the bow shock or the boundary layer for instance, the measurement signal must be rebuilt numerically. The rebuilding of the signal will be performed in analogy to the prediction of the measurement signal described in [22]. Based on a numerical simulation of the flow field, the emission and absorption coefficients for each cell of the numerical grid will be calculated using the plasma radiation data base PARADE [29]. To obtain the radiation impinging on the senor head, the radiation transport must be calculated. As a further benefit, the flow field simulations represent a connection to the 14 other payloads aboard EXPERT.

Beyond the mere identification of the radiating species, the rebuilt signals now allow for quantitative analysis of the plasma state. Primary goals are the spatially resolved species distribution and excitation temperatures. The excitation temperatures need to be extracted from the numerical simulations because the spectral resolution is too low for extraction from line profiles. In case several atom emission lines from one species are detected, temperatures could also be gained from line ratios.

The comparison of measurement data and numerical data provides an approach to validate the current status of the chemical and radiation models implemented in the numerical tools. The numerically predicted measurement signals, dominated by NO and O_2 and showing some atomic oxygen emission lines, give reason to the conclusion that the validation will focus on oxygen chemistry and radiation.

Depending on the finally available flight data and results of the post flight analysis, further steps could be required. Examples might be the development of more sophisticates QSS (quasi steady state) models for radiation calculation in non-equilibrium flows or the implementation of diffusion models for erosion products and corresponding chemical models in the CFD codes used for flow field simulation. The existence of erosion products would show up in the recorded spectra by a sudden increase of the corresponding emission line. Furthermore, this feature could be used to detect active erosion on the ceramic C/C-SiC heat shield of the EXPERT nose. The feasibility of this method was demonstrated by Herdrich in plasma wind tunnel experiments [24].

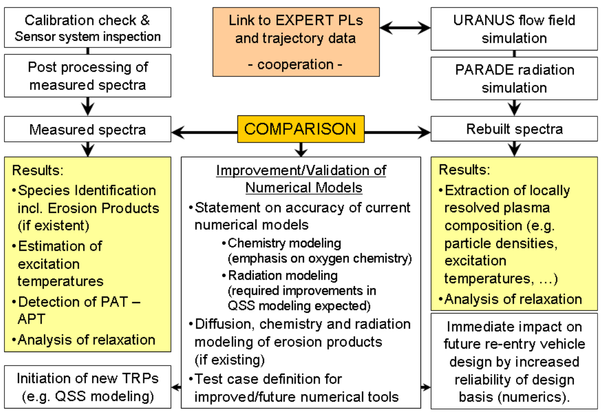

Fig. 2. Outline of RESPECT post flight analysis.

An outline of the RESPECT post flight analysis is shown in Fig. 2. It is expected that the comprehensive data base built by the EXPERT payloads, consisting of a large variety of different experiments, will yield a new test case for coupled flowfield/radiation simulations. The measurements along the EXPERT trajectory, described in section 3.1, will complement the available data from the FIRE, BSUV and UVDE experiments. The EXPERT flight fills the gap between the FIRE high-speed, high-altitude data and the low-speed, low-altitude flight regime of the BSUV experiment. Beyond this, the experiment benefits from the progress in both, instrument technology and numerical tools for design and post flight analysis. A further asset is the unique approach to gather data from 14 different payloads in one single flight dedicated to the investigation of aerothermodynamic phenomena.

3.1 The EXPERT Mission

The ESA EXPERT program provides a flight testbed for aerothermodynamic in-flight research [1]. The EXPERT (European eXPErimental Re-entry Testbed) re-entry vehicle, shown in Fig. 3 is a ballistic capsule with a nose radius of 0.55 m and a mass of about m = 436 kg. EXPERT will be equipped with 14 scientific instrumentations [30]. The focus of the IRS involvement, with the payloads PYREX, PHLUX and RESPECT, is on the nonequilibrium gas-phase physics which needs to be considered in numerical modelling. Major topics are thermo-chemistry, radiation and gas-surface interaction.

Fig. 3. EXPERT with RESPECT SH positions marked.

It is planned to launch the vehicle in 2012 from a submarine in the Pacific Ocean on top of a Russian Volna rocket. Parachute landing is planned on the Kamchatka peninsula. The trajectory data is plotted in Fig. 4. The entry velocity is scheduled to $v_e = 5$ km/s and a peak heat flux of 1.7 MW/m^2 at the stagnation point is expected. Thus, the trajectory is significantly different from the hyperbolic entries of FIRE I and FIRE II. Convective heat flux is significantly lower and an appreciable radiation heat flux is not expected.

The flow conditions are more comparable to the UVDE bow shock experiment, characterized by a velocity of about 5.1 km/s in the altitude range above 62 km.
The spectroscopic instrument RESPECT will be fully operational before reaching an altitude of 100 km. Deactivation is planned at an altitude of 20 km. Continuous measurements with a changing measurement frequency, depending on the changing radiation intensity along the trajectory, are planned for the operational period.

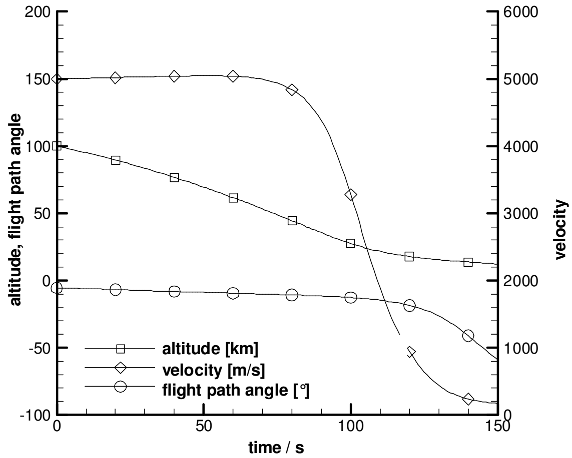

Fig. 4. EXPERT re-entry trajectory data.

3.2 RESPECT Sensor System Design

The payload can be subdivided into two major hardware segments. The first hardware segment is represented by the sensor heads. The sensor heads contain an optical system to collect the radiation emitted by the plasma. The radiation is then transmitted via fibre optic cables to the spectrometer units in the sensor unit (SU), which is the second hardware segment. Here the measurement data is processed and stored on internal flash memory devices. Additionally a hardware segment on vehicle side is required to provide power. In case of EXPERT it is represented by the power control and distribution unit (PCDU). Optionally, based on the overall data handling strategy of the mission, a data acquisition system can be connected to the payload. For the EXPERT mission, RESPECT transfers measurement and housekeeping data to the vehicle onboard data handling system (OBDH) and vehicle memory unit (VMU). The schematic set-up of the RESPECT sensor head and the functional chain are shown in Fig. 5.
The sensor unit (SU) is the central element of the payload and contains all electronic components, which are designed around the spectrometers representing the core component of the experiment. The design is based preferably on COTS components in order to reduce

development effort and costs. As most of the components are not space qualified, pre-testing and modification of the COTS elements was a significant part of the development process. To be compliant with the mechanical loads of the EXPERT launch and re-entry, the controller units and spectrometers, especially the CCD mounting, were modified and reinforced.

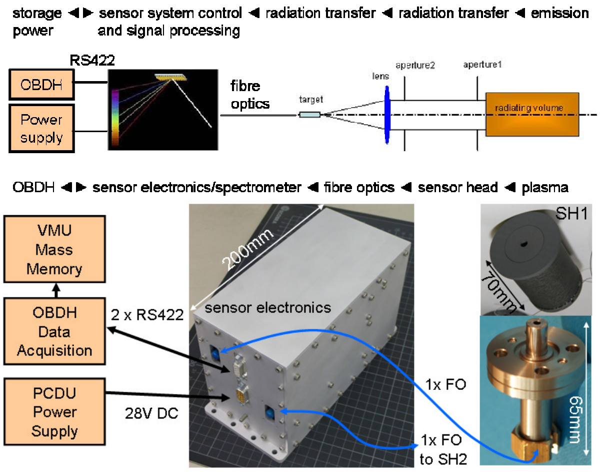

Fig. 5. Set-up of the RESPECT sensor system.

Two miniaturized spectrometers of type OceanOptics S2000 were chosen for their robustness while being still lightweight and small. The spectrometer was tested intensely at IRS in pre-tests and in the qualification test campaign [25, 26]. Further proof of the suitability of the chosen spectrometers is given by independent tests performed by CEA [27]. The OceanOptics S2000 is a miniaturized UV/VIS spectrometer in Czerny-Turner configuration using a 600 lines/mm fixed grating for dispersing incoming radiation on a 2048 pixel linear CCD. The commercially available spectrometer control and data acquisition unit was replaced by a self developed control system dedicated to autonomous in-flight operation. Consequently, after power-on the sensor electronics boots automatically and starts operation. The basis of the spectrometer control system is a Portux920T single board PC with an ARM920T core working at 180 MHz, onboard interfaces for communication and onboard support for SD flash cards, which are used for internal storage of the measurement data. The Portux920T provides an embedded Linux operating system which supports the execution of C++ programs. Such a program was developed to control the spectrometer units including exposure time control based on real-time data processing. Further electronic components are 12 bit A/D converters to digitize the spectrometer signals and a power conditioning board to provide all electronics components with their individual voltage level. In addition, RS422 links are included in the electronics design to allow for bidirectional communication with the EXPERT OBDH via RS422 links. Dedicated commands for data acquisition, internal mass memory management, including resetting and formatting of the disk space, and payload shutdown are implemented. The two channel electronics designed for EXPERT, including the spectrometers, has a nominal power consumption of 3.5 W.

The application of an optical measurement method induces the need of optical access to the measurement object, i.e. the plasma of the post shock regime. Thus, optical ports are required to be included in the TPS of the vehicle. These ports are represented by the sensor heads (SH) of the payload, which were designed to be part of TPS system. SH1 is located in the stagnation area of the vehicle and hence is integrated into the ceramic C/C-SiC heat shield of the EXPERT vehicle [28]. SH2 is embedded in one of the two PHLUX sensor inserts and placed 653 mm along the vehicle axis downstream the stagnation point. The sensor heads of the payload must be designed in order to fit in the TPS system at the SH position and according to the thermal and mechanical loads expected. This leads to different design solutions for the two sensor head position.

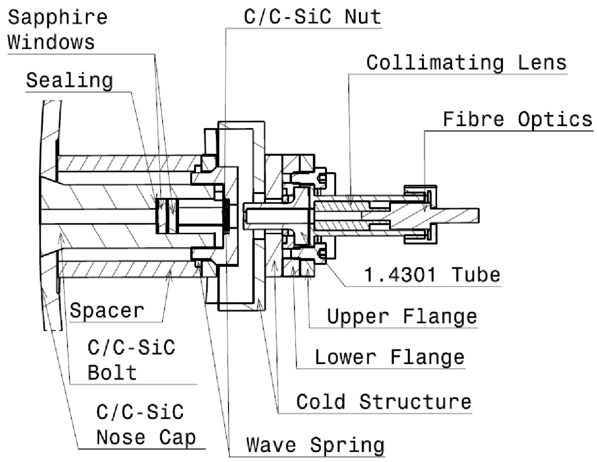

Fig. 6. Sectional view of SH1.

In addition, the required optical properties must be taken into account. For both sensor heads they are defined primarily by the collimating lens and the aperture characteristics of each sensor head.

The design of SH1, shown in Fig. 6, is divided in two major assemblies. The outer part of the sensor head, which creates the optical access by means of an integrated sapphire window, is build of C/C-SiC components made by DLR Institute of Structures and Design and is embedded in the ceramic heat shield [28]. The inner part of SH1 represents the optical system and is mounted to the cold structure. The rough dimensions of SH1 are 135 mm in length and 42 mm in diameter.

The window is held in place by C/C-SiC components. The design constitutes of a threaded bolt with countersunk head that is inserted into the nose from the outside. To have a pre-load on the bolt, a metallic spring is used which is located at the cold end of the assembly. The bolt is fixed with a nut that is at the same time exerting pressure on the sapphire window panes. The window is located at a distance from the hot surface that is large enough so as not to overheat and deteriorate its optical properties. The inner part consists basically of a flange accommodating a collimating lens system and a metal tube to protect the optical path. The tube protects the optical path from intruding obstacles, i.e. possible debris from the thermal insulation. The tip of the tube is formed as an aperture which acts as an essential part of the optical design to adjust the sensor to the expected radiation intensity levels.

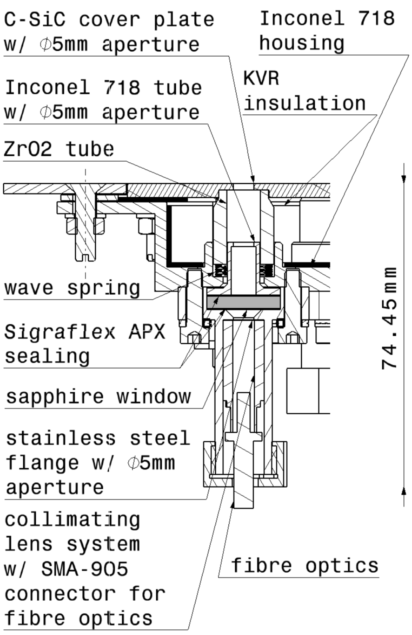

Fig. 7. Sectional view of SH2.

SH2, shown in Fig. 7, is similarly designed. An exception is the subdivision into two assemblies, which is not applied in the design of SH2. The division in two structures without rigid connection was expandable due to the lower thermal loads at the position of SH1.

The design of both, sensor unit and sensor heads, is tested extensively. Single key components, e.g. the spectrometers or the SH1 design, have already been tested in the development phase of the payload. The EXPERT payload qualification test campaign consisted of mechanical, thermal, EMC, functional and plasma wind tunnel tests [26]. Especially, the mechanical loads have been very challenging due to the characteristics of the Russian Volna launcher. Nevertheless, all qualification tests were passed successfully as well as the acceptance tests of the flight model.

The key parameters of the payload RESPECT are summarized in Table 2. Regarding the measurement specifications, the system provides some advantages in comparison to the FIRE and BSUV/UVDE instruments. The lower wavelength limit of 200 nm, defined by the beginning VUV spectral range, is the same as for the previous experiments. But, in particular in comparison to the BSUV/UVDE spectrometers, a significant extension towards longer wavelengths could be achieved by a comparable spectral resolution. Another advantage is the non-scanning type spectrometer, which minimizes the influence of changing flight conditions, e.g. altitude or density respectively, on a recorded spectrum.

Payload Parameters (2 Measurement Channels)			
	SU	**SH1**	**SH2**
mass / kg	1,95	0.18	0.1
dimensions / mm	200x130x 100	∅ 42 length 65	∅ 35 length 75
power consumption	3.5 W (input voltage 28 V DC +/- 5 V)		
data rate	3082 byte per spectrum		
RS422 data link polling frequency	1.66 Hz per RS422 link		
RS422 data link transfer rate	115200 bps per RS422 link		
flash storage capacity	2 Gb per measurement channel		
Measurement Specifications			
wavelength range	200 nm – 850 nm		
pixel resolution	0.35 nm		
FWHM	1.5 nm		
exposure time	1 ms – 242 ms		
measurement rate	up to 15 Hz		

Table 2. RESPECT payload parameters and measurement specifications.

3.3 Future Developments

As the payload is newly developed, design is based on the interface specifications and requirements of EXPERT. In particular, due to their high level of integration into the TPS concept, the sensor heads need to be redesigned if an application of the payload on other missions/vehicles is aspired. However, for RESPECT aboard EXPERT two different sensor head design for integration in ceramic and metallic TPS are already developed, which can serve as a basis for future designs. Furthermore, the measurement layout results from the EXPERT trajectory and mission sequence. Nevertheless, the sensor system, and especially the sensor unit, can be adapted to other mission. The exposure time control in combination with the aperture design of the sensor heads allows operation in wide range of radiation intensity. In particular, re-entry conditions providing higher radiation levels are unproblematic, and even desired from a scientific point of view. The application of the sensor system for a different trajectory even in a different atmosphere requires basically only a new layout in terms of intensity, meaning adaption of aperture diameters and exposure time limits. The spectral range and spectral resolution can be changed by very minor modifications to the S2000 spectrometers. The modifications are limited to the grating and the entrance slit width, which do not change the general spectrometer design. Different standardized entrance slit and grating configurations are available from OceanOptics.

Unfortunately, the extension of the spectral range towards VUV would require a more fundamental redesign of the payload. The variety of commercially available miniaturized spectrometers capable of detecting VUV radiation is still poor, which limits the chance to find suitable models. Nevertheless, OceanOptics fabricates now the Maya type series miniaturized spectrometers operating in the spectral range beginning at 165 nm. However for a reasonable interpretation of VUV, the spectral range should be extended to about 100 nm, where both nitrogen and oxygen influences can be studied. An even more radical concept for a re-design of the system would be the application of custom made VUV spectrometers on basis of different spectrometer types such as Rowland or Echelle. Echelle spectrometers allow a comparably high spectral resolution and high frame rates over a still wide wavelength range. Further challenges when aiming on VUV radiation concern the optical path. As no VUV fibres are available a direct light transmission has to be realized. This causes the spectrometers to be placed closer to the measurement position in the TPS.

Further options for future revisions of the sensor system are the development of a single channel version or the implementation of a battery. The single channel version would result in a significantly lighter, smaller and less power consuming version, which could be applied to missions with smaller payload budget. The estimated volume of the one channel versions gives about half of the current volume. Weight and power budget could be cut almost by the factor of two. The implementation of a battery would yield a stand alone system without any electrical or power interface to the vehicle.

Apart from the typical application of the system for studying aerothermodynamics during atmospheric entry or re-entry, the system could be adapted to problems with a similar challenging environment. An example is the integration in SCRAMJET combustion chambers for monitoring combustion chemistry.

4. SUMMARY

A brief review of the past in-flight and airborne experiments applying optical emission spectroscopy to measure spectrally resolved the radiation emitted by the plasma surrounding a space vehicle during re-entry was given. The measurement objective, applied instrumentation and the measurement specifications regarding instrument performance and flight regime are summarized. The first of these experiments was performed in the frame of project FIRE, which was primarily motivated by the necessity to demonstrate hyperbolic re-entry in a test flight. Nevertheless, the data recorded by the spectrometer and the radiometers are still used as a test case for coupled flowfield/radiation simulations. The later on performed experiments BSUV and UVDE aimed primarily on gathering spectral data to support the chemistry and radiation modelling applied in numerical tools. Furthermore, these experiments extended the data basis available towards lower speed and lower altitude. The experiment RESPECT, developed for EXPERT, follows the same objective. One of the prime goals of the EXPERT mission with its 14 scientific payloads is to build a database on in-flight data related to critical phenomena of atmospheric entry, and thus providing a comprehensive test case for different numerical tools. EXPERT, equipped with the IRS system RESPECT, the first European spectrometer system for re-entry application, fills the gap between the FIRE high-speed, high-altitude data and the low-speed, low-altitude flight regime of the BSUV experiment. Beyond this, the experiment benefits from the progress in both, instrument technology and numerical tools for design and post flight analysis.

Although, by considering the data of all these in-flight experiments, a data base containing data from a large variety of flight regimes is available for validation of numerical tools, future emission spectroscopic and radiometer experiments are highly desirable. It was outlined that in particular VUV experiments are missing.

The presented spectroscopic and radiometer experiments have been used to study re-entry in Earth's atmosphere without exception. Considering the improvements in chemical and radiation modelling enabled by these measurements, the application of spectrometer experiments in other planetary entry scenarios is most desirable.

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